CONSTRAINING LORENTZ VIOLATION PARAMETERS WITH ICECUBE (GEN2)MEASUREMENT OF ASTROPHYSICAL NEUTRINO FLAVOR RATIOS

K.-C. Lai, W.-H. Lai and GLL in preparation

OUTLINE

1. Introduction
2. Lorentz violation effects to neutrino flavour transitions
3. Lorentz violation and current IceCube data on astrophysical neutrino flavour composition
4. IceCube Gen2 and its potential of constraining Lorentz violation parameters
5. Summary and conclusion

INTRODUCTION

- Violations of Lorentz symmetry could arise in string theory V. A. Kostelecky and S. Samuel, Phys. Rev. D 39, 683 (1989)
  V. A. Kostelecky and R. Potting, Nucl. Phys. B 359, 545 (1991)
- The effects of Lorentz violations (LV) to neutrino oscillations have been studies before

  V. A. Kostelecky and M. Mewes, Phys. Rev. D 69, 016005 (2004)
  V. A. Kostelecky and M. Mewes, Phys. Rev. D 70, 031902 (2004)
  V. A. Kostelecky and M. Mewes, Phys. Rev. D 70, 076002 (2004)

- The standard model neutrino Hamiltonian in vacuum

$H_{\mathrm{SM}} \equiv U M^2 U^\dagger / 2E$ with

$$M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

U : PMNS matrix

H_{SM} behaves as $1/E$

- With Lorentz violation

$$H \equiv H_{\mathrm{SM}} + H_{\mathrm{LV}}$$

H_{LV} contains E^0 and E^1 terms

- Standard neutrino oscillation probability depends on *L/E*
- Lorentz violation introduces *L* and *LE* terms. It also generates directional dependence due to the breaking of rotation symmetry
- Experiments probing LV focus on (i) spectral anomalies of the oscillated neutrino flux, (ii) sidereal variations of neutrino oscillation probabilities.

Short baseline beams (1-4), long baseline beams (5-6), reactor neutrino (7-8), atmospheric neutrinos in IceCube (9) and Superkamiokande (10)

(1) L. B. Auerbach *et al*. [LSND Collaboration], Phys. Rev. D 72, 076004 (2005).
(2) P. Adamson *et al*. [MINOS Collaboration], Phys. Rev. Lett. 101, 151601 (2008).
(3)A. A. Aguilar-Arevalo *et al*. [MiniBooNE Collaboration], Phys. Lett. B 718, 1303 (2013).
(4) P. Adamson *et al*. [MINOS Collaboration], Phys. Rev. D 85, 031101 (2012).
(5) P. Adamson *et al*. [MINOS Collaboration], Phys. Rev. Lett. 105, 151601 (2010).
(6) B. Rebel and S. Mufson, Astropart. Phys. 48, 78 (2013).
(7) Y. Abe et al. [Double Chooz Collaboration], Phys. Rev. D 86, 112009 (2012).
(8) J. S. Diaz, T. Katori, J. Spitz and J. M. Conrad, Phys. Lett. B 727, 412 (2013).
(9) R. Abbasi *et al*. [IceCube Collaboration], Phys. Rev. D 82, 112003 (2010).
[10] K. Abe *et al*. [Super-Kamiokande Collaboration], Phys. Rev. D 91, no. 5, 052003 (2015).

- We shall study the LV effects with high energy astrophysical neutrino source. The neutrino flavour transition probability this case is

$$P(\nu_\alpha \to \nu_\beta) = |V_{\alpha i}|^2 |V_{\beta i}|^2,$$

where V is the matrix that diagonalises the full Hamiltonian

$$H = H_{\rm SM} + H_{\rm LV}$$

$1/E$ E^0 and E^1

- V approaches to PMNS matrix U for $H_{\rm LV}$=0.
- We the neutrino energy is sufficiently high, the structure of V is dictated by $H_{\rm LV}$.

$$H = H_{\mathrm{SM}} + H_{\mathrm{LV}}$$

$1/E$ E^0 and E^1

The structure of H_{SM}

For simplicity, taking $\theta_{23} = 45^\circ,\ \theta_{13} = 0$

$$H_{\mathrm{SM}} = \begin{pmatrix} s_{12}^2 \frac{\Delta m_{21}^2}{2E} & \frac{\sqrt{2}}{2} s_{12} c_{12} \frac{\Delta m_{21}^2}{2E} & -\frac{\sqrt{2}}{2} s_{12} c_{12} \frac{\Delta m_{21}^2}{2E} \\ \frac{\sqrt{2}}{2} s_{12} c_{12} \frac{\Delta m_{21}^2}{2E} & \frac{1}{2}\left(c_{12}^2 \frac{\Delta m_{21}^2}{2E} + \frac{\Delta m_{31}^2}{2E}\right) & \frac{1}{2}\left(-c_{12}^2 \frac{\Delta m_{21}^2}{2E} + \frac{\Delta m_{31}^2}{2E}\right) \\ -\frac{\sqrt{2}}{2} s_{12} c_{12} \frac{\Delta m_{21}^2}{2E} & \frac{1}{2}\left(-c_{12}^2 \frac{\Delta m_{21}^2}{2E} + \frac{\Delta m_{31}^2}{2E}\right) & \frac{1}{2}\left(c_{12}^2 \frac{\Delta m_{21}^2}{2E} + \frac{\Delta m_{31}^2}{2E}\right) \end{pmatrix}$$

Large values at 2nd and 3rd rows
and columns—special flavour structure μτ symmetry

Flavour structure of H_{LV} may differ significantly from H_{SM}

Detectable from the flavour composition of astrophysical neutrinos reaching to the Earth

Common astrophysical neutrino sources

(1) *pp* collisions: roughly the same number of π^+ and π^- are produced.

$$\pi^+(\pi^-) \to \mu^+(\mu^-)\nu_\mu(\bar{\nu}_\mu)$$

$$\mu^+(\mu^-) \to \nu_\mu(\bar{\nu}_\mu)e^+(e^-)\bar{\nu}_e(\nu_e)$$

(a) secondary muons decay immediately

Pion source

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 1/6 : 1/6 : 1/3 : 1/3 : 0 : 0$$

(b) secondary muons lose significant energies before decay

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 0 : 0 : 1/2 : 1/2 : 0 : 0$$

Muon-damped source

(2) $p\gamma$ collisions: produce mainly π^+

$$p + \gamma \to \Delta^+ \to n + \pi^+$$

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$$

(a) secondary muons decay immediately

Pion source

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 1/3 : 0 : 1/3 : 1/3 : 0 : 0$$

(b) secondary muons lose significant energies before decay

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 0 : 0 : 1 : 0 : 0 : 0$$

Muon-damped source

LV EFFECTS TO NEUTRINO FLAVOUR TRANSITIONS

For neutrinos, the general form of LV Hamiltonian

$$H^{\nu}_{\rm LV} = \frac{p_\lambda}{E}\begin{pmatrix} a^{\lambda}_{ee} & a^{\lambda}_{e\mu} & a^{\lambda}_{e\tau} \\ a^{\lambda*}_{e\mu} & a^{\lambda}_{\mu\mu} & a^{\lambda}_{\mu\tau} \\ a^{\lambda*}_{e\tau} & a^{\lambda*}_{\mu\tau} & a^{\lambda}_{\tau\tau} \end{pmatrix} - \frac{p^\rho p^\lambda}{E}\begin{pmatrix} c^{\rho\lambda}_{ee} & c^{\rho\lambda}_{e\mu} & c^{\rho\lambda}_{e\tau} \\ c^{\rho\lambda*}_{e\mu} & c^{\rho\lambda}_{\mu\mu} & c^{\rho\lambda}_{\mu\tau} \\ c^{\rho\lambda*}_{e\tau} & c^{\rho\lambda*}_{\mu\tau} & c^{\rho\lambda}_{\tau\tau} \end{pmatrix}$$

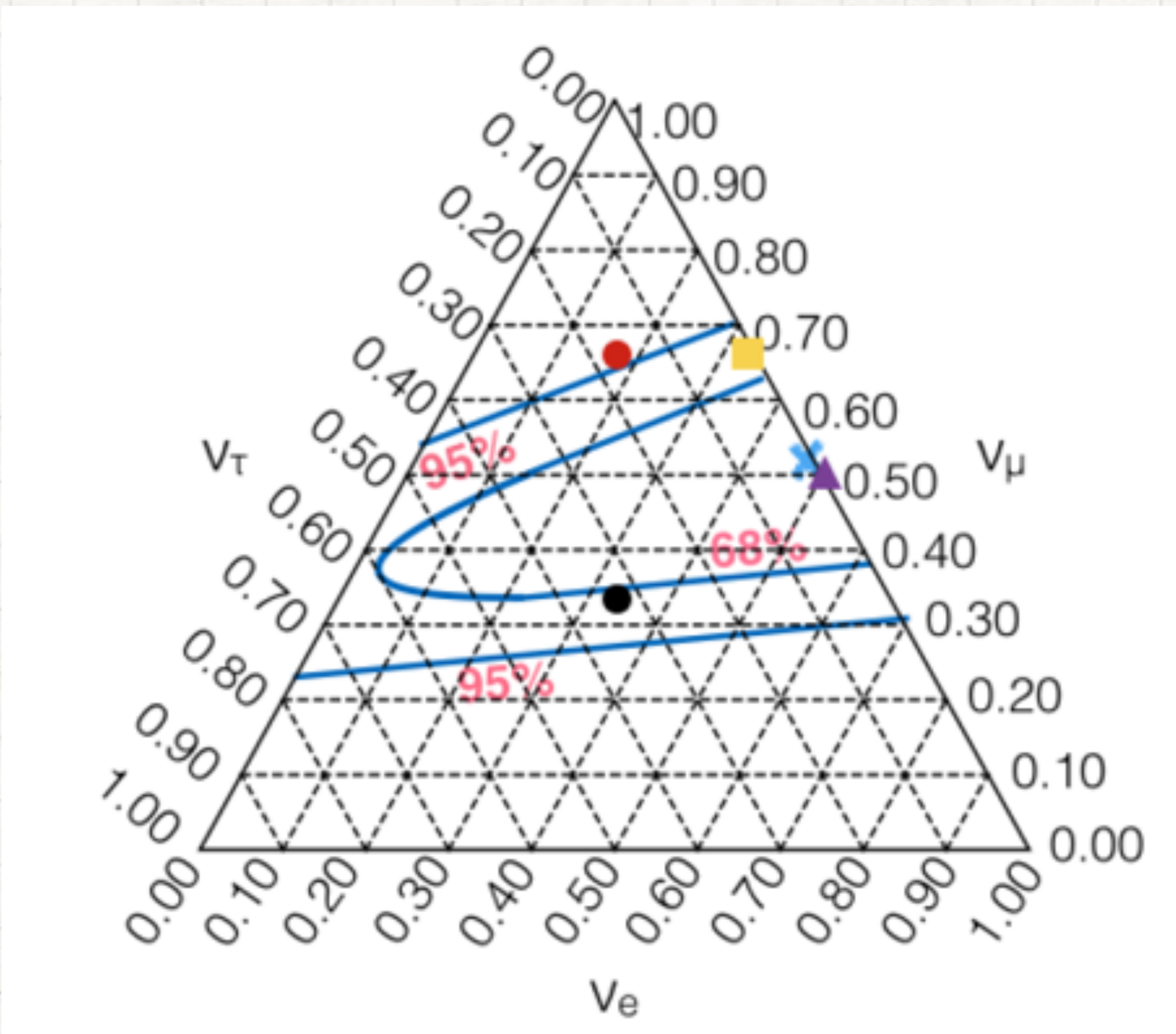
For rotationally invariant LV effects

$$H^{\nu}_{\rm LV} = \begin{pmatrix} a^{T}_{ee} & a^{T}_{e\mu} & a^{T}_{e\tau} \\ a^{T*}_{e\mu} & a^{T}_{\mu\mu} & a^{T}_{\mu\tau} \\ a^{T*}_{e\tau} & a^{T*}_{\mu\tau} & a^{T}_{\tau\tau} \end{pmatrix} - \frac{4E}{3}\begin{pmatrix} c^{TT}_{ee} & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ c^{TT*}_{e\mu} & c^{TT}_{\mu\mu} & c^{TT}_{\mu\tau} \\ c^{TT*}_{e\tau} & c^{TT*}_{\mu\tau} & c^{TT}_{\tau\tau} \end{pmatrix} \qquad H^{\bar\nu}_{\rm LV} = -\begin{pmatrix} a^{T}_{ee} & a^{T}_{e\mu} & a^{T}_{e\tau} \\ a^{T*}_{e\mu} & a^{T}_{\mu\mu} & a^{T}_{\mu\tau} \\ a^{T*}_{e\tau} & a^{T*}_{\mu\tau} & a^{T}_{\tau\tau} \end{pmatrix}^{*} - \frac{4E}{3}\begin{pmatrix} c^{TT}_{ee} & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ c^{TT*}_{e\mu} & c^{TT}_{\mu\mu} & c^{TT}_{\mu\tau} \\ c^{TT*}_{e\tau} & c^{TT*}_{\mu\tau} & c^{TT}_{\tau\tau} \end{pmatrix}^{*}$$

$(T,\ X,\ Y,\ Z)$ Sun-centered celestial equatorial frame

Let us first focus on $a^{T}_{\alpha\beta}$

LORENTZ VIOLATIONS AND CURRENT ICECUBE RESULTS ON ASTROPHYSICAL NEUTRINO FLAVOUR RATIOS



E_ν is between 25 TeV and 2.8 PeV

$H_{SM} \approx \Delta m^2_{31}/2E_\nu$

Hence H_{SM} is between

$$5 \times 10^{-26}\ \mathrm{GeV}$$

and

$$4.5 \times 10^{-28}\ \mathrm{GeV}$$

M. G. Aartsen et al. [IceCube Collaboration], Astrophys. J. 809, no. 1, 98 (2015)

Can Lorentz violation play role in this data?

CURRENT BOUNDS ON LORENTZ VIOLATION PARAMETERS SUPERKAMIOKANDE MEASUREMENTS

LV parameter		Limit at 95% C.L.	Best fit	No LV $\Delta\chi^2$	Previous limit
$e\mu$	$\mathrm{Re}(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [61]
	$\mathrm{Im}(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	$\mathrm{Re}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [61]
	$\mathrm{Im}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [62]
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17} [62]
	$\mathrm{Im}(c^{TT})$	1.0×10^{-24}	3.5×10^{-25}		
$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	...
	$\mathrm{Im}(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	...
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}		

$$H_{SM} < 5 \times 10^{-26}\ \mathrm{GeV}$$

K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D 91, no. 5, 052003 (2015).

Significant room for H_{LV} to play an important role

SPECIAL STRUCTURES OF H_{LV} AND THE RESULTING ASTROPHYSICAL NEUTRINO FLAVOUR COMPOSITION ON EARTH

$$H_{\mathrm{LV}}^{\nu} = \begin{pmatrix} t_1 & r_1 e^{i\psi_1} & r_2 e^{i\psi_2} \\ r_1 e^{-i\psi_1} & t_2 & r_3 e^{i\psi_3} \\ r_2 e^{-i\psi_2} & r_3 e^{-i\psi_3} & t_3 \end{pmatrix} \qquad H_{\mathrm{LV}}^{\bar{\nu}} = - \begin{pmatrix} t_1 & r_1 e^{-i\psi_1} & r_2 e^{-i\psi_2} \\ r_1 e^{i\psi_1} & t_2 & r_3 e^{-i\psi_3} \\ r_2 e^{i\psi_2} & r_3 e^{i\psi_3} & t_3 \end{pmatrix}$$

t_1 can be set to zero

(A) only r_1 is non-vanishing (not counting the phases)

$$P = \begin{pmatrix} 1/2 & 1/2 & 0 \\ 1/2 & 1/2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = |V_{\alpha i}|^2 |V_{\beta i}|^2,$$

$$\Phi(\nu_e) : \Phi(\nu_\mu) : \Phi(\nu_\tau) = 1/2 : 1/2 : 0$$

SPECIAL STRUCTURES OF H_{LV} AND THE RESULTING ASTROPHYSICAL NEUTRINO FLAVOUR COMPOSITION ON EARTH

(B) only r_3 is non-vanishing

$$P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix}$$

$$\Phi(\nu_e) : \Phi(\nu_\mu) : \Phi(\nu_\tau) = 1/3 : 1/3 : 1/3$$

SPECIAL STRUCTURES OF H_{LV} AND THE RESULTING ASTROPHYSICAL NEUTRINO FLAVOUR COMPOSITION ON EARTH

(C) only r_2 is non-vanishing

$$P = \begin{pmatrix} 1/2 & 0 & 1/2 \\ 0 & 1 & 0 \\ 1/2 & 0 & 1/2 \end{pmatrix}$$

$$\Phi(\nu_e) : \Phi(\nu_\mu) : \Phi(\nu_\tau) = 1/6 : 2/3 : 1/6$$

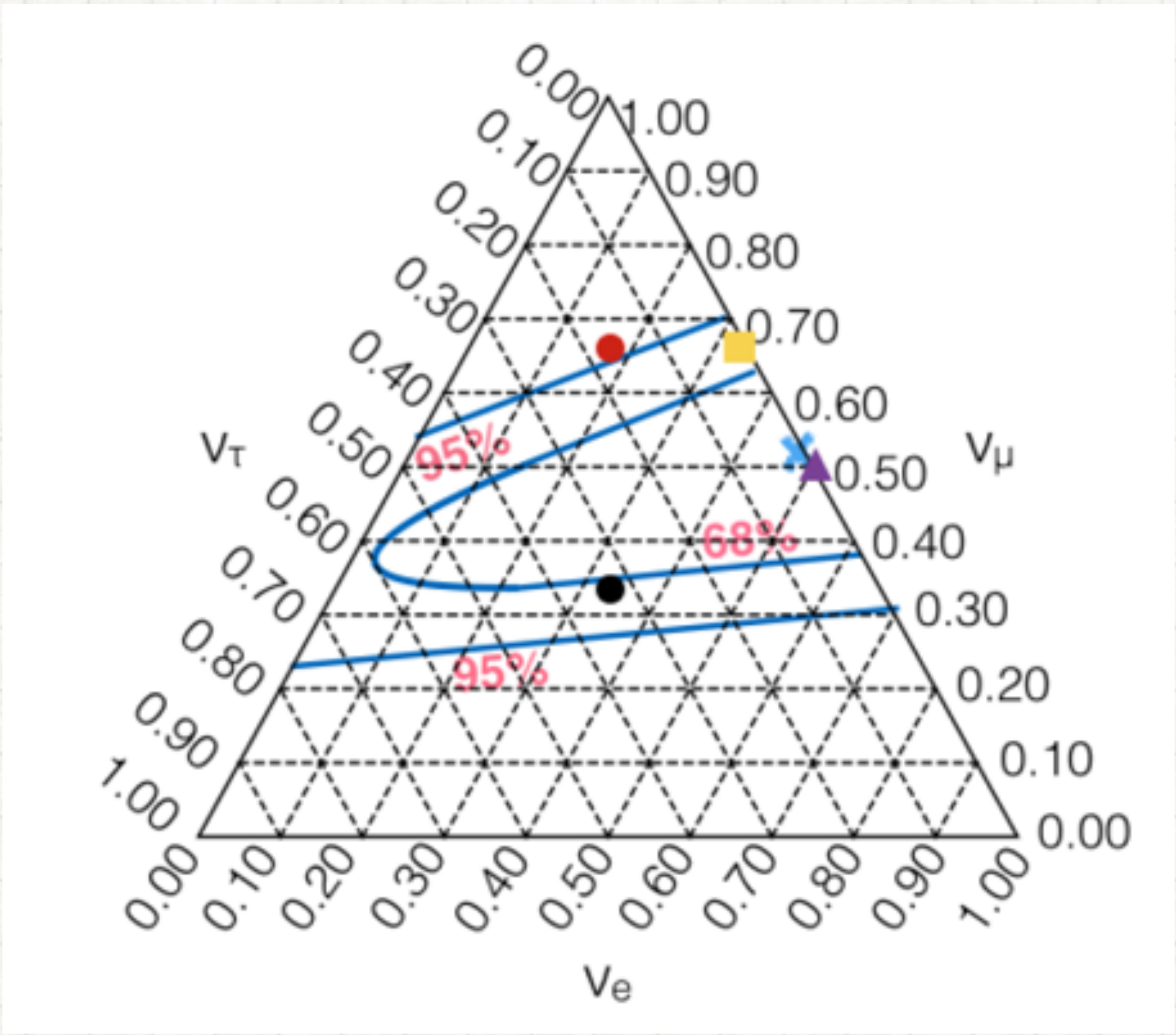
SPECIAL STRUCTURES OF H_{LV} AND THE RESULTING ASTROPHYSICAL NEUTRINO FLAVOUR COMPOSITION ON EARTH

(D) only t_2, t_3 are non-vanishing

$$P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Phi(\nu_e) : \Phi(\nu_\mu) : \Phi(\nu_\tau) = 1/3 : 2/3 : 0$$

COMPARISONS OF SPECIAL CASES WITH RECENT ICECUBE MEASUREMENT OF ASTROPHYSICAL NEUTRINO FLAVOUR COMPOSITION



Red: $a_{e\tau}, a^*_{e\tau} \neq 0$

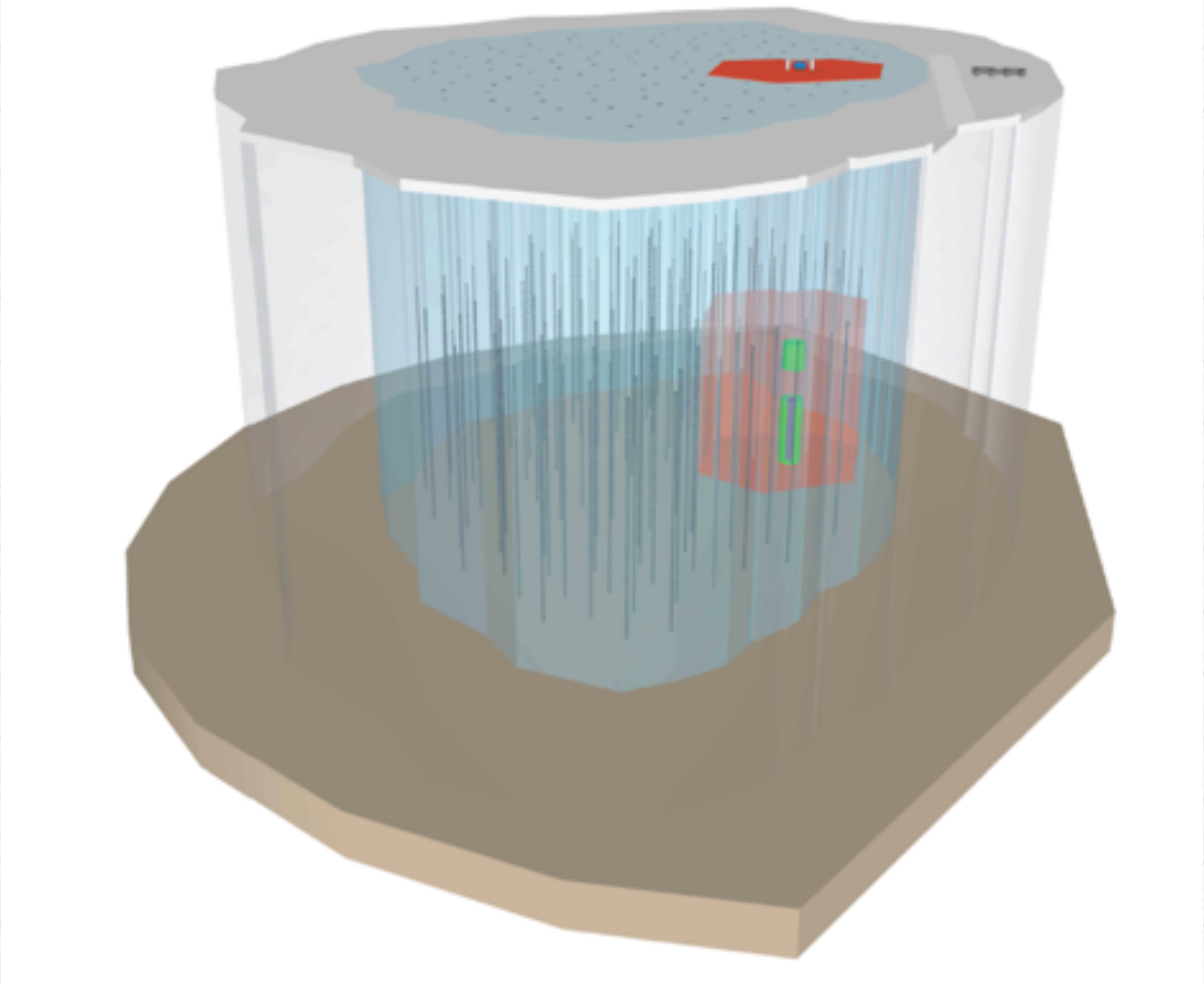
Yellow: $a_{\mu\mu}, a_{\tau\tau} \neq 0$

Purple: $a_{e\mu}, a^*_{e\mu} \neq 0$

Black: $a_{\mu\tau}, a^*_{\mu\tau} \neq 0$

All cases fall into 2σ region as other elements grow from zero

ICECUBE GEN2 AND ITS POTENTIAL OF CONSTRAINING LORENTZ VIOLATION PARAMETERS



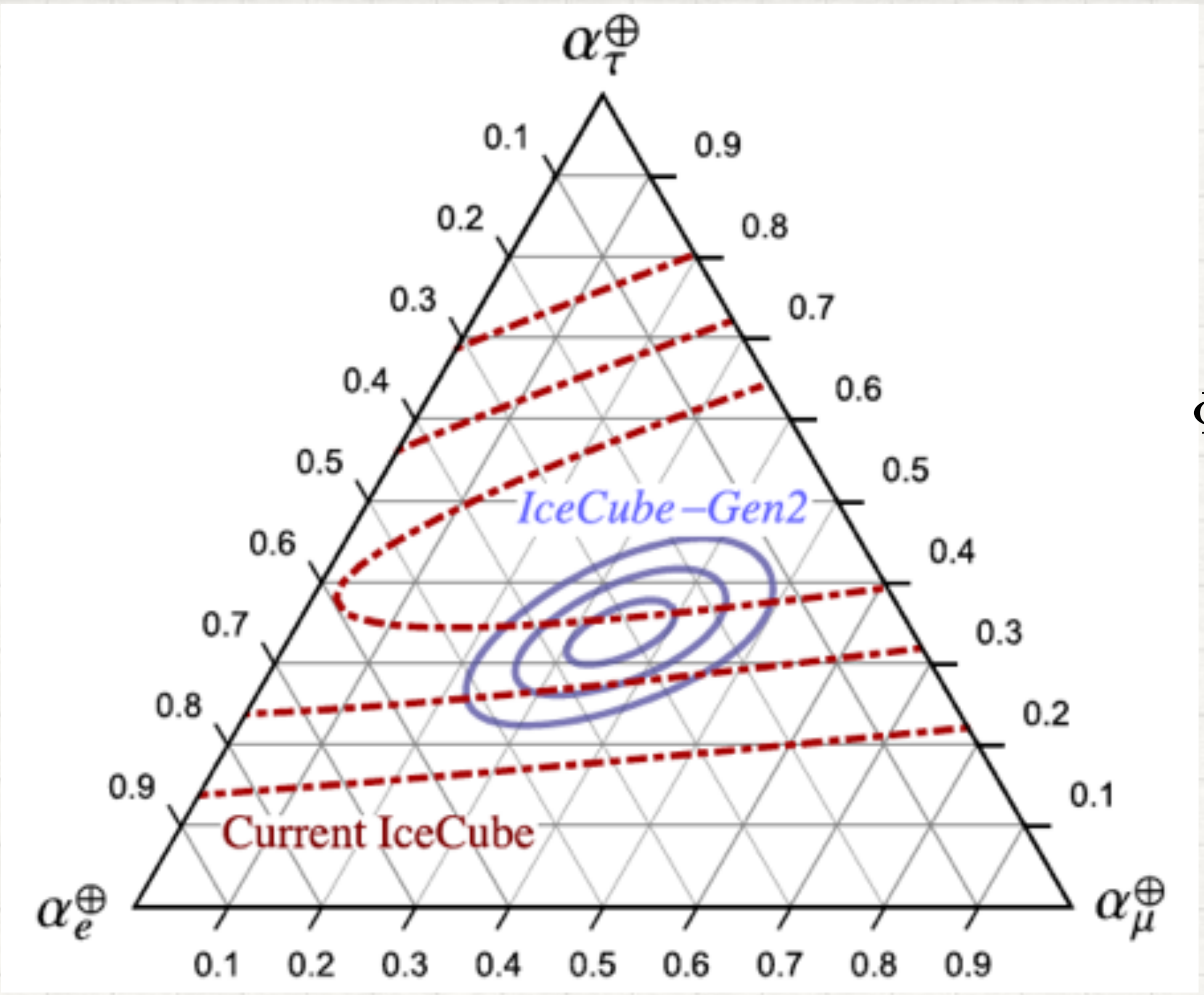
IceCube Collaboration (M.G. Aartsen (Adelaide U.) et al.), arXiv:1412.5106

~10 km^3 instrumented volume

~250 m spacing of photo sensors

A possible IceCube-Gen2 configuration. IceCube, in red, and the infill sub-detector DeepCore, in green, show the current configuration. The blue volume shows the full instrumented next-generation detector, with PINGU displayed in grey as a denser infill extension within DeepCore.

SENSITIVITIES OF ICECUBE-GEN2 ON ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITIONS



$$\Phi_\nu(E) = \Phi_0 \left(\frac{100\ \text{TeV}}{E}\right)^\gamma$$

$$\gamma = 2.2 \pm 0.2$$

$$\Phi_0 = (5.1 \pm 1.8) \times 10^{-18} \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

Pion source is assumed

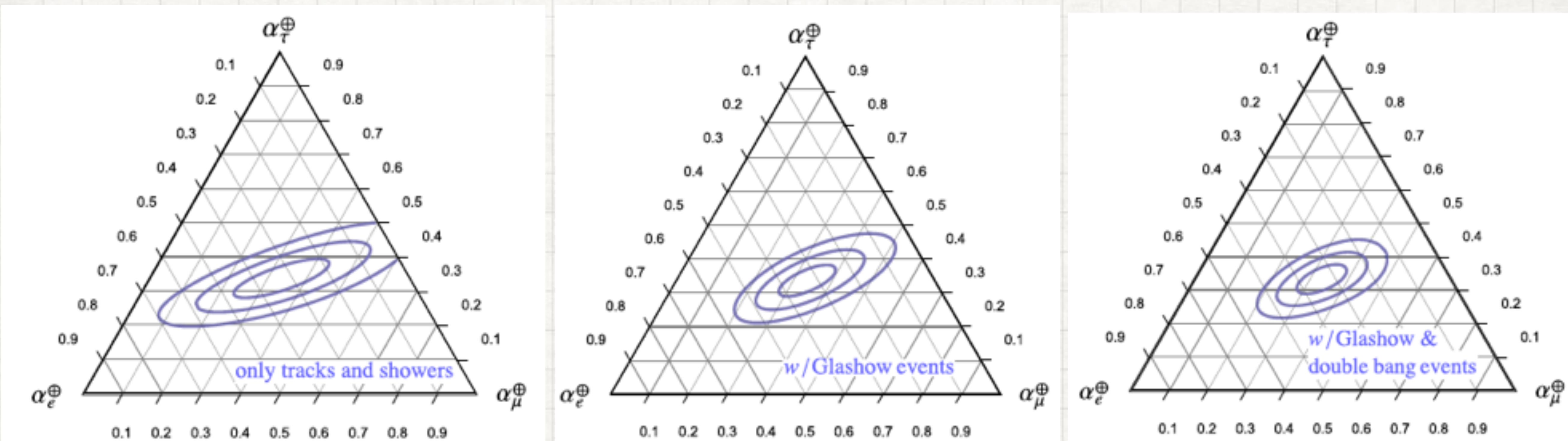
$$E_{\text{th}} = 100\ \text{TeV}$$

10 years of exposure

1σ, 2σ, and 3σ regions

I. M. Shoemaker and K. Murase, Phys. Rev. D 93 085004 (2016)

SENSITIVITIES OF ICECUBE-GEN2 ON ASTROPHYSICAL NEUTRINO FLAVOR COMPOSITIONS



I. M. Shoemaker and K. Murase, Phys. Rev. D 93 085004 (2016)

Types of neutrino events

Track Events & Cascade Events

Track Events

Charged-Current ν_μ interaction : $\nu_\mu + N \rightarrow \mu^- + X$

Cascade Events

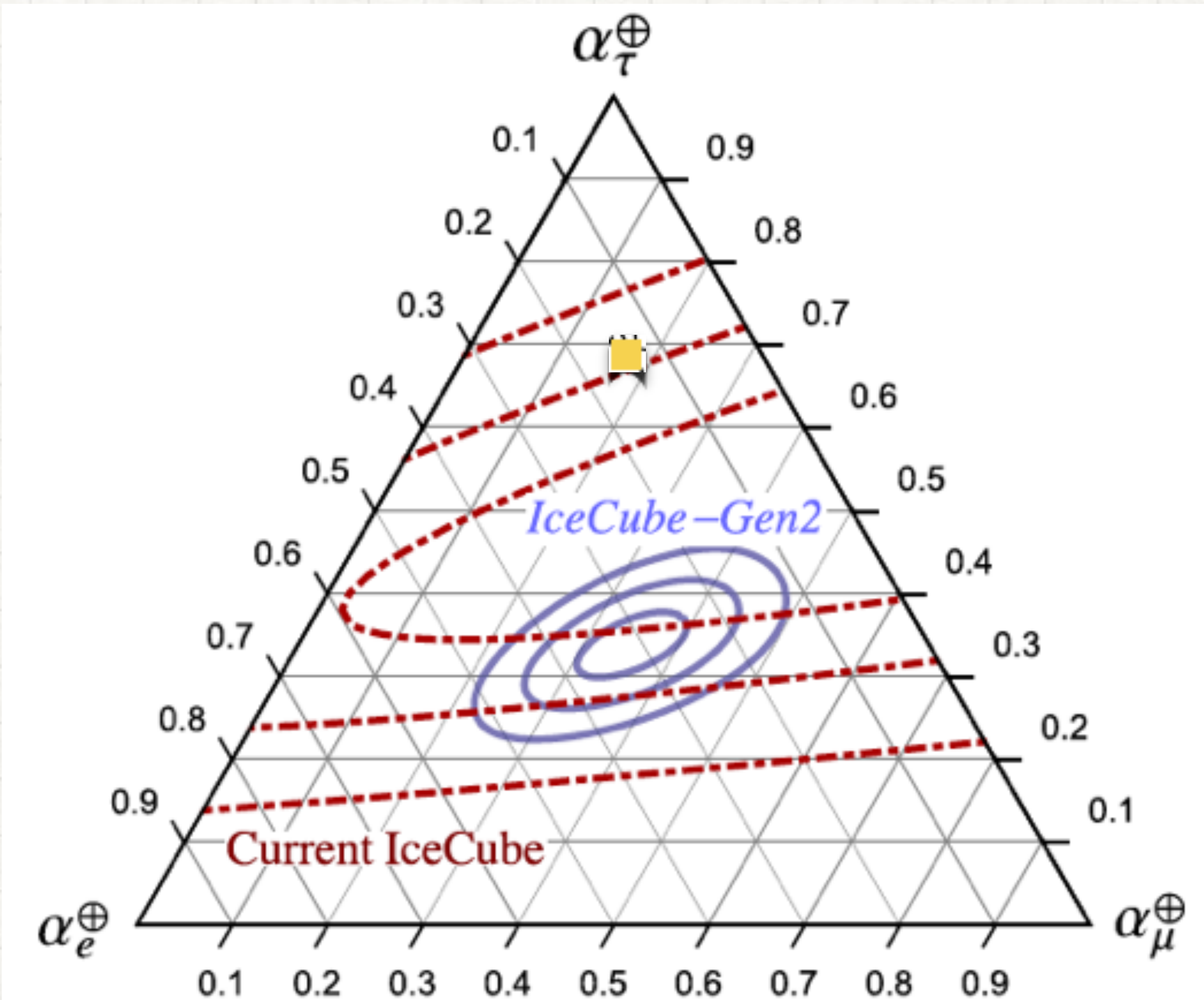
Neutral-Current ν_l interaction : $\nu_l + N \rightarrow \nu_l + X$ (Hadronic)

Charged-Current ν_e interaction : $\nu_e + N \rightarrow e^-$ (EM) $+ X$ (Hadronic)

Charged-Current ν_τ interaction : $\nu_\tau + N \rightarrow \tau^- + X$

Double bang events: tau decay shower distinguished from CC int.

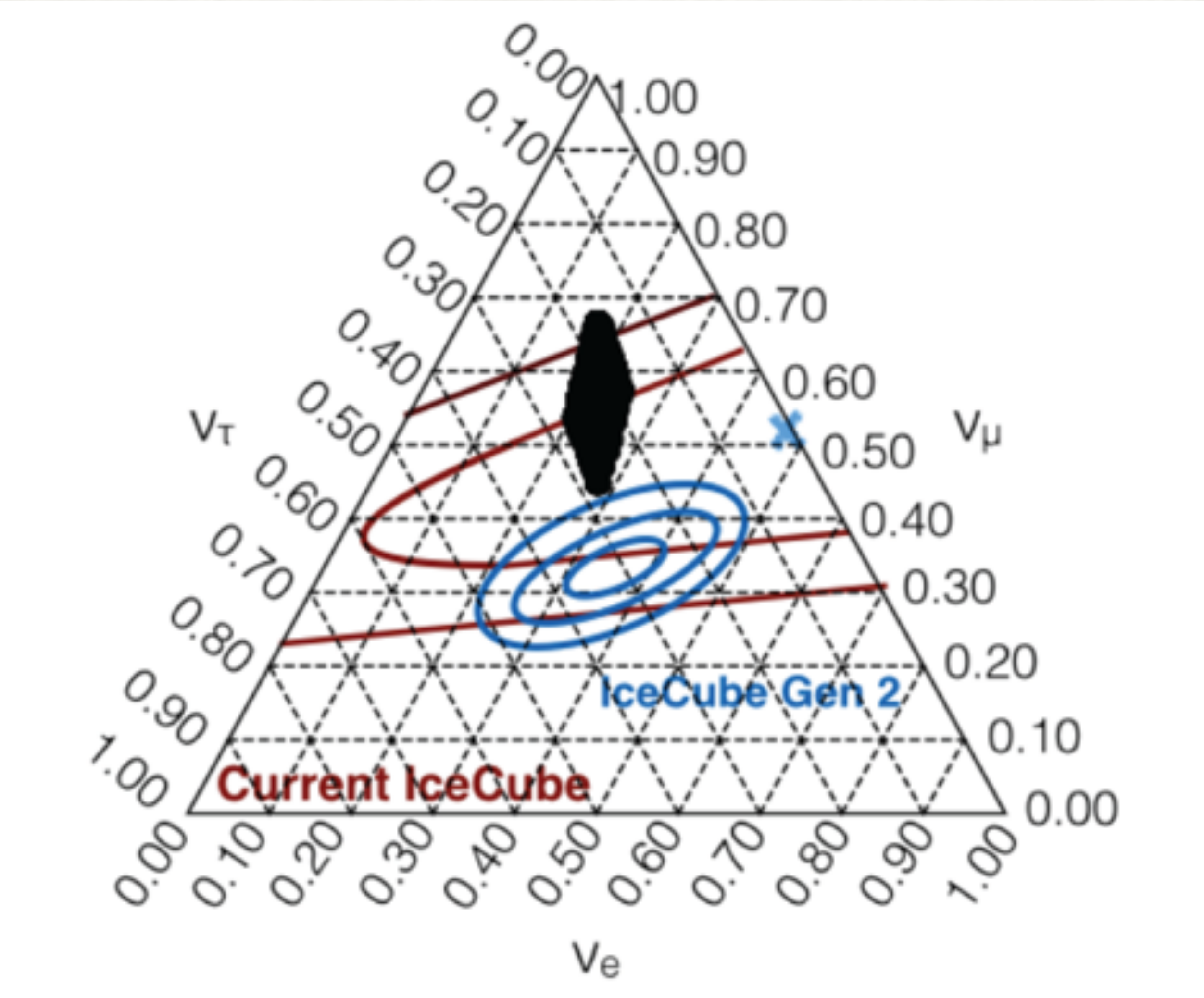
Glashow resonance: $\bar{\nu}_e e^- \rightarrow W^- \rightarrow l\bar{\nu}_l, q\bar{q}'$



Yellow square corresponds to the following structure

$$\begin{pmatrix} 0 & 0 & a^T_{e\tau} \\ 0 & 0 & 0 \\ a^{T*}_{e\tau} & 0 & 0 \end{pmatrix}$$

Allow other elements to grow from zero and add H_{SM}



SK limit for $|a^T_{e\tau}|$ 5×10^{-23} GeV

$|a^T_{e\tau}|$ largest energy scale

$H_{SM} <$ 1.2×10^{-26} GeV

$$\tilde{a}_{\alpha\beta} = a^T_{\alpha\beta} + a^{\rm SM}_{\alpha\beta}$$

$$0 \le x, y, z \le 0.35$$

$$x = |\tilde{a}_{e\mu}|/|\tilde{a}_{e\tau}|, y = |\tilde{a}_{\mu\tau}|/|\tilde{a}_{e\tau}|,$$
$$z = |\tilde{a}_{\tau\tau}|/|\tilde{a}_{e\tau}|. \text{ Insensitive to } \tilde{a}_{\mu\mu}$$

Phase of each element is allowed to vary from 0 to 2π

The above parameter ranges of LV can be excluded at 3σ or we detect something beyond standard 3-flavor oscillation

SUMMARY AND CONCLUSIONS

- We have introduced Lorentz violation Hamiltonian in neutrino sector and discuss its effect on neutrino oscillations.
- Previous experimental search on Lorentz violation with neutrino is introduced. Previous best limit by SuperKamiokande experiment is summarised.
- We argue that, even with SK limit, Lorentz violation effect can still play an important role on flavour transitions of high energy astrophysical neutrino in TeV to PeV energy range.
- We show that IceCube-Gen2 can place stringent constraints on the flavour structure of Lorentz violation.